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Our Ref: P 42734 US

21 October 2003
EW/rc/ne

Phase shifting wavefront superimposition method

The invention relates to a phase shifting wavefront
superimposition method, in which the intensity of
5   superimposition patterns of object wavefronts and
reference wavefronts produced successively in time with
respective phase shifts by predefinable phase steps is
registered for a respectively predefinable location
and, from the registered intensities, an object-induced
10 phase difference between the object and reference
wavefronts at this location is determined.

Wavefront superimposition methods of this type are
usual, for example using Moiré techniques and two-beam
15 interferometer or shearing interferometry techniques.
One important area of application relates to measuring
high-resolution optical imaging systems with regard to
aberrations, such as projection objectives for
microlithography projection exposure installations for
20 semiconductor wafer structuring.

Typically, the superimposition patterns of object and
reference wavefronts, produced by such methods,
comprise a normally strip-like spatial intensity
25 distribution pattern, the intensity being modulated
periodically by phase shifting.   The phase is

determined separately at the individual locations from appropriate mathematical relationships. By means of suitable selection of the method parameters involved, such as period number and step number, and of what are
5   known as apodisation weights, which can be represented as complex numbers and describe the influence of the intensity value of each measurement step on the phase at the relevant location, systematic errors, such as undersampling, harmonics and scaling errors of a phase
10 shifter used can generally be suppressed adequately. High frequency vibrations, which can occur in the measurement structure, are averaged out, normally with a loss of contrast, and are only of subordinate importance, as long as they are considerably faster
15 than the measurement or exposure time. In the same way, drift phenomena can be neglected, as long as they are considerably slower than the entire measurement or exposure time.

20 Conventional methods of the type mentioned at the beginning, including familiar associated error correction methods are described, for example, in the textbook by D.Malacara, Optical Shop Testing, 2nd ed, John Wiley & Sons, Inc., 1992 and in the literature
25 cited there, to which reference can be made for further details, see in particular the chapters about Moiré techniques and phase shifting interferometry, like Chapter 14 with the heading "Phase Shifting Interferometry".
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As opposed to high frequency vibrations and drift phenomena, stochastic phase step errors which, for example, are caused by low frequency vibrations in the measurement structure or control fluctuations or
35 oscillations from the surroundings, impair the measurement accuracy significantly.

The invention is based, as a technical problem, on the provision of a phase shifting wavefront superimposition

method of the type mentioned at the beginning which, with relatively little outlay, offers a comparatively high measurement accuracy, even given the occurrence of stochastic phase step errors which fall into the

5   measurement time window and which, for example, result from low frequency vibrations in the measurement structure.

The invention solves this problem by providing a phase

10   shifting wavefront superimposition method of the type mentioned at the beginning wherein, to determine the object-induced phase difference, phase step errors which occur in the superimposition patterns produced successively are taken into account correctively, the

15   phase step errors being determined by means of a spatial superimposition pattern evaluation.

The method according to the invention in this way combines the technique of time phase shifting which, as

20   is known, offers high resolution and therefore measurement accuracy, with the technique of spatial evaluation of the typically strip-like superimposition patterns, the last-named technique being comparatively insensitive with respect to time fluctuations in the

25   time window of the measurement time. By means of the spatial superimposition pattern evaluation, any phase step errors of the phase shifting operation are determined and are then taken into account correctively in the evaluation of the phase shifting operation.

30   Alternatively or additionally to a strip pattern evaluation, the superimposition pattern evaluation can include the measure of predefining specific initial phase variations in the object wavefront and/or the reference wavefront.

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The method according to the invention can be implemented both as a Moiré technique and also as an actual interferometry technique in the narrower sense of the word, the intention being in the present case

for simplicity for the term "phase shifting interferometry" also to cover the corresponding Moiré techniques. For the method according to the invention, both techniques with stepwise phase shifting and techniques with continuous phase shifting can be used.

In an advantageous development of the invention, predefined phase jumps in a one-dimensionally or multi-dimensionally periodic structure are used to produce the object wavefront or the reference wavefront when determining the phase step errors. By means of a suitable selection of these phase jumps, the strip density for the spatial superimposition evaluation can be set in a defined manner, in order to make the spatial strip evaluation easier and in order to prevent very many strips making the evaluation more difficult.

In a further configuration of the invention, the corrective action of taking the phase shift error into account includes a compensating determination of corrective contributions to apodisation weights in the mathematical functional relationship of the object-induced phase difference as a function of the superimposition pattern intensities.

Advantageous embodiments of the invention are illustrated in the drawings and will be described below. Here:

fig. 1   is a flowchart of a phase shifting wavefront superimposition method with phase step error correction,

fig. 2   is a plan view of a linear grid with predefined phase jumps for producing object or reference wavefronts in the method of fig. 1,

fig. 3   is a schematic, perspective view of a detail of an interferometer mirror with predefined phase jumps for producing object or reference wavefronts in the method of fig. 1,

fig. 4   is a plan view of a detail of a parquet grid
         with predefined phase jumps for producing
         object or reference wavefronts in the method of
         fig. 1, and

5   fig. 5   is a view corresponding to fig. 4 for a
            checkerboard grid variant.

The method of which the sequence is illustrated
schematically in fig. 1 is based on superimposing
10 wavefronts by means of a phase shifting interferometry
or Moiré measuring technique, forming a corresponding
superimposition pattern, also referred to as an
interferogram in the present case.   The interfering
wavefronts can, for example, be produced in an
15 interferometer or by means of diffraction at Moiré
grating structures.   The method may be used in
particular for the highly precise measurement of high-
resolution imaging systems with regard to imaging
errors, such as aberrations or distortion errors.   The
20 method can be used specifically for highly accurate
imaging error determination in high-resolution
projection objectives in microlithographic projection
exposure installations, for which purpose appropriate
apparatus is known in the prior art and therefore
25 requires no further explanation, see for example,
measurement apparatus based on shearing interferometry,
as disclosed in the laid-open specification
DE 101 09 929 A1 and the German patent application
102 17 242.0 from the applicant, which is not a prior
30 publication.   In such measuring apparatus, the optical
imaging system to be measured functions as an object,
so that the object wavefront supplied by it carries the
imaging error information which then, following
superimposition of the object wavefront with the
35 reference wavefront, can be extracted from the
superimposition pattern as object-induced phase
difference information.

As usual, in phase shifting wavefront superimposition methods, the intensity I_n of an interferogram for a respective phase step n is modulated periodically by a phase shift increment $\varphi_n = 2\pi np/N$, with the parameters period number p and step number N. The phase φ is determined separately at each individual location from a suitable mathematical relationship which can normally be traced back to an equation of the form

$$\phi = \arg \sum_{n=1}^{N} \omega_n I_n$$

with what are known as apodisation weights ω_n, which represent complex numbers. By means of a suitable selection of the parameters comprising period number p and step number N and the complex apodisation weights ω_n, systematic errors, such as undersampling, harmonics and scaling errors of a phase shifter used in the associated apparatus can be suppressed adequately. Furthermore, high-frequency vibrations, which are considerably faster than the exposure time, that is to say the measurement time, and also drift phenomena, which are considerably slower than the entire measurement time, can be neglected. On the other hand, the measurement accuracy is influenced considerably by stochastic phase step errors $\delta\varphi_n$, as are caused in the measurement structure, for example by low frequency vibrations or control fluctuations or coupling with non-steady state environment.

The method shown in fig. 1 is used to register such phase step errors $\delta\varphi_n$ and to take them into account correctively when determining the object-induced phase difference. In the application of measuring optical imaging systems, in this way the influence of such phase step errors $\delta\varphi_n$ on the imaging error information to be obtained by evaluation of the object-induced phase difference can be compensated for, completely or in any case partially.

In a first method step 1, the interferogram intensities I_n and the phase step errors $\delta\varphi_n$ are registered. No such high requirements need to be placed on the accuracy of the registration of the phase step errors $\delta\varphi_n$ as on the determination of the actual phase φ, since the errors are propagated sufficiently weakly in the evaluation of the initial phase.

Therefore, to register the phase step errors, it is sufficient to determine spatially the phase in the interferogram from the superimposition pattern, typically a corresponding strip pattern. This can be done, for example, in accordance with the known four-step formula, in that, in the above equation, instead of the phase step index, use is made of an index n' of the spatial coordinate of the p/N-th fraction of a strip (or other feature of the spatial superimposition pattern) and, for example, the period number p = 1 and the step number N = 4 with complex apodisation weights $\omega_{n'} = i^{n'}$ are selected, that is to say the index n' relates to spatial phase variation (strip pattern) and the index n relates to time phase variation (phase shifting). The difference between the nth phase from the superimposition pattern and the expected nth phase shift gives the searched-for phase step error $\delta\varphi_n$.

This difference has to be determined at at least one location in the superimposition pattern. In the case of tilting in the interferogram, a plurality of location reference points are needed. Ideally, a linear profile is expected, which is determined by means of linear regression over the entire field of the superimposition pattern. If non-linear profiles are expected, for example as a result of aberrations in the optical imaging system to be measured, these are determined by means of suitably adapted regression.

In some applications, it may be that many strips can occur in the superimposition pattern and disrupt the

actual measurement task, or that the strip density cannot be set accurately enough for the spatial evaluation. In such cases, the method includes the use of periodic structures for producing the object and/or

5   reference wavefronts, said structures having defined phase jumps at at least one location in the field of the superimposition pattern. Exemplary possible implementations of such periodic structures with defined $\pi/2$ phase jumps are illustrated in figs. 2 to

10   4. Other predefined phase jumps are also possible, for example fractions of an integer period $2\pi\cdot p'/N'$ (with period number p' and step number N').

Fig 2 shows a diffraction grating in the form of a one-

15   dimensionally periodic line grid 4, the term "one-dimensionally" meaning that grid lines, symbolized by light and dark lines in fig. 2, are arranged following one another in only one direction, from top to bottom in fig. 2. A central square region of the line grid 4

20   is subdivided into four square subregions 4a, 4b, 4c, 4d, in which the line pattern is offset by defined phase jumps with respect to the surrounding line pattern. Specifically, in the bottom left subregion 4b, the line pattern is offset downward by $\pi/2$ as

25   compared with the unshifted line pattern in the top left subregion 4a. The line pattern in the top right subregion 4d is offset upward by a phase jump of $\pi/2$ as compared with the unshifted line pattern in the top left subregion 4a. The line pattern in the bottom right

30   subregion 4c is offset downward by a phase jump of $\pi/2$ as compared with the line pattern in the bottom left subregion 4b and, consequently, by a phase jump of π as compared with the surrounding outer line pattern.

35   Fig. 3 shows schematically an interferometer mirror 5 which, in appropriate subregions 5a, 5b, 5c, is provided with layer additions for implementing respective $\pi/2$ phase jumps. Specifically, the layer addition shown in a front left subregion 5a effects a

phase jump of π/2 as compared with the uncovered mirror surface. The layer addition twice as thick in a rear right subregion in turn effects a phase jump of π/2 as compared with the front left subregion 5a and therefore

5   of π as compared with the uncovered mirror surface. The thickness of the layer addition in a rear left subregion 5c corresponds to three times the thickness of the layer addition in the front left subregion 5a and consequently implements a phase jump of 3π/2 or

10   -π/2 as compared with the uncovered mirror surface. Instead of elevations, depressions of the layer are also possible. The layers can also have outlines other than square ones.

15   The π/2 phase jumps described above in relation to the examples of figs. 2 and 3 are suitable in particular for the four-step method. For other method variants, other, suitable phase jumps can be implemented as required in an analogous way. The production of

20   suitable phase jumps in respective subregions of a periodic structure is also possible in multi-dimensionally periodic structures, that is to say in structures which have periodically successive structure elements in a plurality of directions,

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Fig. 4 shows, as an example of an application of this type, a two-dimensionally periodic diffraction grating in the form of a parceled parquet grid 6. The parquet grid 6 comprises two groups of square regions arranged

30   alternately in the manner of parquet, a first group 7a to 7d with vertical grid lines in fig. 4 and a second group 8a to 8d with horizontal grid lines in fig. 4. In conventional parquet grid structures, the grid lines of the parquet squares are in phase among themselves in

35   one group. Differing from this, in the parquet group 6 of fig. 4, the grid lines of each of the two groups are offset with respect to each other from one to the next parquet square, both in the horizontal direction and in the vertical direction, in each case by a phase jump of

π, the line patterns of each two diagonally adjacent parquet squares of the same group being offset by a phase jump of π/2. In other words, in fig. 4, the vertical grids lines of the associated four parquet

5   squares 7a to 7d in this order of the four squares are phase shifted by π/2 in each case in the counterclockwise direction and in the clockwise direction and this is correspondingly true of the grid lines of the four parquet squares 8a to 8d with

10   horizontal grid lines in order in the counterclockwise direction and in the clockwise direction. The initial phases in the parquet cells can also be assigned in a different order. Likewise, other phase jumps can be selected instead of π/2.

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Figure 5 shows a variant with a checkerboard grid 9 as a two-dimensionally periodic diffraction grating with a plurality of parcels with offset checkerboard patterns. As can be seen from figure 5, the square checkerboard

20   grid 9 is subdivided into four square parcels which have the same checkerboard pattern, but the checkerboard pattern being offset in a defined way, that is to say the result for the checkerboard grid 9 is defined initial phases and thus phase jumps in a

25   manner analogous to the parquet grid 6 of figure 4.

After the phase step errors $\delta\varphi_n$ have been determined in this way, the same are taken into account in a compensating manner in the evaluation of the initial

30   phases in a next step 2 of the method sequence according to fig. 1. For this purpose, in an advantageous implementation of the method, the apodisation weights ω_n are modified by means of additive correction contributions $\delta\omega_n$ in such a way that,

35   irrespective of which initial phase is present, the complex Fourier sums do not change. In other words, the correction contributions $\delta\omega_n$ of the apodisation weights ω_n are determined from the following conditional

equation, which applies to all the intensity values $I(\varphi)$:

$$\sum_{n=1}^{N}(\omega_n + \delta\omega_n)I(\phi_n + \delta\phi_n) = \sum_{n=1}^{N}\omega_n I(\phi_n) \qquad \forall I(\phi)$$

In the simplest case, this conditional equation is solved by approximation in linear disturbance theory, which is adequate for small phase step errors $\delta\varphi_n$. For every harmonic component m of the periodic intensity signal

$$I(\varphi) = \sum_m \jmath_m \exp(im\varphi)$$

the modified Fourier sums and the disrupted Fourier sums are compensated, that is to say the following is true:

$$\sum_{n=1}^{N}\delta\omega_n \exp(im\phi_n) + im\sum_{n=1}^{N}\omega_n\delta\phi_n \exp(im\phi_n) = 0 \qquad \forall m,$$

which gives the apodisation weight correction contributions $\delta\omega_n$ in the form

$$\delta\omega_n = -\frac{i}{N}\sum_{n'=1}^{N}\omega_{n'}\delta\phi_{n'}\sum_m m\exp(im(\phi_{n'} - \phi_n))$$

Because of the Nyquist condition $-N/2p < m \leq N/2p$, the above determining equation for the apodisation weight correction contributions $\delta\omega_n$ is under-determined. From the many-valued solution, in the present case that one is specified which, with the effect of regularization, that is to say the lowest buildup of errors, sets the subgroups of modified weight values equal. In the same way, weighting with the magnitude $|\omega_n|$ is also possible, for example. As a further alternative, additional secondary conditions can be used which arise from the measurement task, in order to reduce the level of under-determination.

Following the determination of the correction contributions $\delta\omega_n$ to the complex apodisation weights ω_n, in a final method step 3, the actual phase φ and

therefore the object-induced phase difference between object and reference wavefronts for the respective location can be determined from the associated relationship as a function of the modified apodisation weights and the interferogram intensities. This phase information can be used further as required, for example in the context of a measurement of an optical imaging system for highly accurate determination of imaging errors, such as distortion and other aberrations. For this purpose, the chronologically successive phase shifts between object and reference wavefront needed for the phase shifting wavefront superimposition method are performed successively in time, for example in accordance with one of the conventional multi-step methods of a phase shifting interferometry technique (PSI).

As the above description of an advantageous embodiment makes clear, the method according to the invention combines the technique of time phase shifting, which offers comparatively high resolution, with spatial superimposition pattern evaluation, which is comparatively insensitive with respect to fluctuations within typical measurement periods. By means of the spatial superimposition pattern evaluation, phase shifting errors are determined, which are then corrected in the evaluation of the results from the phase shift measurements. The superimposition pattern formation comprises both the possibility of producing typical strip patterns and the use of specific initial phase variations in an appropriate object and/or reference structure, as are implemented, for example, in advanced parquet grid structures. The invention comprises both methods which are based on Moiré techniques and also those which employ actual interferometry techniques, such as lateral shearing interferometry. Furthermore, the invention comprises both variants with stepwise and also those with continuous phase shifts.